Abstract

Interactions in 2% 3% 20% 20% are also reported.

with yields greater than 0.2% for stopping muon.Muon capture
understood in 30% 30% 90%. No candidate gamma have been found
excluded by the atomic cascade of a muon or due to nuclear
search for the gamma decay of nuclear shape resonances.

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Shawn Penrose University, Burnaby, B.C., Canada V5A 1S6
O. Marrese
and
TRIUMF, 400 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3
J. J. McDonald

University of California and Lawrence Berkeley Laboratory,
S. Miyama and V. Misra

Canada V5A 2T2

University of Victoria, P.O. Box 1700, Victoria, B.C.
S. Arais, G. V. Rebi, S. K. Arai, and A. Ohn

Search for the Gamma Decay of Nuclear Resonances.
1. Introduction

In the atomic cascade of a muonic atom formed in an actinide nucleus there is a finite probability of a radiationless (1,2) muonic transition that excites a shape isomeric state (3-6) characterized by increased nuclear deformation. Decay of the shape isomeric state may occur by tunneling through either the inner or the outer barriers of a double-humped fission barrier (7). Penetration of the outer barrier leads to delayed isomeric fission, whereas tunneling through the inner barrier is followed by gamma de-excitation to the ground state through levels in the inner potential well. Calculations predict a higher outer than inner barrier for nuclei having $Z < 94$, which suggests a more penetrable inner barrier for lower $Z$ actinides (7). Shape isomers with lifetimes of about 165 ns in $^{236}$U and 290 ns in $^{238}$U have been observed in normal uranium atoms through the fission decays, whereas searches for the gamma decay mode have yielded inconsistent results (8-12). Searches have also been made for shape-isomeric gamma decay mode of muonic uranium (4,5,13,14). Evidence of such decay in $^{238}$U at a yield of 0.5%/muon stop was reported by Fromm et al. (5). The 12±2 ns lifetime of the muonic shape isomer was attributed to the reduction of the potential barrier due to the presence of the 1s muon. In view of this interesting result, a measurement with greater sensitivity was undertaken for the gamma decay mode of muonic $^{236}$U and $^{238}$U shape isomers.

2. Experimental method

The experiments were performed using the electrostatically separated negative muon beam from the TRIUMF M9 stopped π/μ channel (15). A schematic of the experimental setup is shown in Fig. 1. Absorber D was used to slow the muons and to stop contaminant pions in the beam. The thickness of the absorber was adjusted to maximize muon stops in the uranium target. The uranium targets were 1.7 gm/cm$^2$, >99.5% enriched ($^{238}$U); 2.0 gm/cm$^2$, >95% enriched ($^{236}$U); and 0.8 gm/cm$^2$, >95% enriched ($^{235}$U). The muon stop signal was obtained from a conventional $S_1S_2S_3S_4$ scintillator telescope. In addition, a large pulse (signifying a slow muon) was required in the thin scintillator $S_3$ immediately upstream of the uranium target (T). Contaminant pions and electrons in the beam were vetoed in the stop signal by a cut on the beam time of flight in the channel. Events for which two muon stops were registered within about 300 ns were rejected.

In an early run, gamma rays were detected by a large volume (15%) intrinsic germanium spectrometer and seven NaI(Tl) scintillators (five 7.6 cm × 7.6 cm and two 5 cm × 5 cm). Later runs were performed using a 20% 80 cm$^3$ Ge(Li), a 10% 40 cm$^3$ intrinsic Ge and three 12.7 cm diam × 15.2 cm long NaI detectors. Both the energy and the time of the gamma rays following a muon stop were recorded on tape via CAMAC by a PDP 11/34 computer. Gamma ray energies were calibrated using $^{60}$Co and $^{24}$Na sources and the measured values of muonic $^{238}$U X rays reported by Coté et al. (18).

3. Data analysis and results

The energy and time information from the Ge and NaI detec-
The Gamma ray yields for a peak of energy E are taken at a peak of energy E. The Gamma ray yields for a peak of energy E are taken at a peak of energy E. The Gamma ray yields for a peak of energy E are taken at a peak of energy E. The Gamma ray yields for a peak of energy E are taken at a peak of energy E. The Gamma ray yields for a peak of energy E are taken at a peak of energy E.

The problem involves the determination of the peak height in the case of the observed Gamma ray peak. The determination of the peak height involves the determination of the peak height in the case of the observed Gamma ray peak. The determination of the peak height involves the determination of the peak height in the case of the observed Gamma ray peak. The determination of the peak height involves the determination of the peak height in the case of the observed Gamma ray peak. The determination of the peak height involves the determination of the peak height in the case of the observed Gamma ray peak.

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\[ P = \frac{\lambda_T^4}{\lambda_T^4 + \lambda_T^2 + \lambda_C^4} \]  

where \( \lambda_C^4 \) is the muon capture rate, \( \lambda_T^2 \) is the back decay rate and \( \lambda_F^4 \) is the fission rate from the isomeric state. Substituting some typical values (5) \( \lambda_T^2 = 2.08 \times 10^7 \text{sec}^{-1} \), \( \lambda_T^4 = 6.4 \times 10^2 \text{sec}^{-1} \) and \( \lambda_C^4 = 1.33 \times 10^7 \text{sec}^{-1} \) and using our value of \( Y_T < 0.2 \text{sec}^{-1} \), we get \( P < 0.3 \text{sec}^{-1} \) per muon stop. Radiationless transitions amount to about 25\% of the muon cascade (19), so that from the upper limit for \( P \) a limit of \( <1.2 \times 10^{-2} \) can be deduced for the excitation of the shape isomeric state during a radiationless transition. This is in good agreement with a recent calculation (6). However a measurement of the reaction \( {}^{235}\text{U}(d,p)\, {}^{236}\text{U} \) found that \( \Gamma_T/\Gamma_g < 1.5 \) for the 165 ns isomer at 2.35 MeV (12), so it is possible that the non-observation of back-decay on our experiment is due to the low probability for such deexcitation.

In addition, we have also studied the time distribution of gammas measured with the NaI detectors in coincidence with prompt muonic \( K_{\alpha} \times \gamma \) rays (shown in Fig. 2) measured with a Ge detector. In principle, this should give the true muon capture lifetime since the contributions from the prompt fission fragments (produced by non-radiative transitions) are eliminated. It is also probable that some of the gamma rays are from secondary interactions in the target of neutrons produced in muon capture, but the time dependence would still follow that of the capture process. Lifetimes thus measured were: 71 \pm 2 \text{ns} ({}^{235}\text{U}), 70 \pm 2 \text{ns} ({}^{236}\text{U}), 78 \pm 2 \text{ns} ({}^{238}\text{U}). The {}^{235}\text{U} \text{ and } {}^{238}\text{U}, \text{ results are in good agreement with previous measurements (16). No previous measurement for } {}^{236}\text{U} \text{ has been reported.}

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References
